Design and analysis of HVDC switch gear station for meshed HVDC grid

Project of Science

PATRICIA SERRANO JIMÉNEZ

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Department of Energy and Environment
Division of Electric Power Engineering
Chalmers University of Technology
SE–412 96 Goteborg¨
Sweden
Telephone +46 (0)31–772 100

ABSTRACT

It is of fundamental interest to avoid faults in a DC grid due to the severely of these events. However, the faults are unavoidable, so in a fault case is necessary to act fast.

The protection in a DC grid comprises a key component, the HVDC breaker. For this reason in this thesis, a simulation is programmed in order to be able to study the HVDC breaker operation, distinguishing between normal and fault operation. Matlab is the program used in this work, and an initial simulation is tested firstly to choose which method is the most appropriate.

Once the circuit behaviour is studied, some tactics to improve the performance of the system are proposed, focusing on thermal losses.

The principal results (current waveforms and energy dissipation) show that introducing some modifications into the system like using more IGBTs in parallel or changing the inductance values, it is possible to get a feasible DC breaker.

To sum up, this report will present one tool being able to simulate different configurations and to study the results, besides some suggestions how to make the system more efficient.

Keywords: HVDC Breaker, IGBT

ACKNOWLEDGEMENTS

I would like to express my special appreciation to Prof. Torbjorn Thiringer for providing me the opportunity to work in this project and for all support guidance and encouragement during the same.

I am also grateful for the support I have received from my family. Especially from my older brother, Daniel, without his help during all my degree anything would have been possible.

Moreover, my gratitude goes to my friends, Isabel and Veronica, who have shared with me unforgettable moments. .

Finally, I have no words to appropriately thank Javier for his invaluable support and understanding. He has been my strength.

CONTENTS

LIST OF SYMBOLS

IGBT	Insulated Gate Bipolar Transistor
Vce	Collector-emitter voltage
Vge	Gate-emitter voltage
Vgg	Gate-gate voltage
Ic	Collector current
$i$aux	Auxiliary current
$i$break	Main current
Itotal	Total current
Z_{th}	Thermal impedance

CHAPTER 1
INTRODUCTION

The development of alternative energy sources using renewable energy is an important environmental step. Offshore wind energy is one of the major upcoming sources of energy.

DC transmission can be preferred in an offshore power transmission due to the reactive power limitation of long AC power transmissions. However DC transmission presents a difficult behaviour when a short-circuit fault occurs, due to the fact that the current has no zero crossing, and also a relatively low impedance due to absence of ωL reactance. The fault penetration is thus deeper in a DC grid. In order to handle this effect, it is necessary to have fast and reliable HVDC breakers to isolate faulted parts. In order to prevent unwanted consequences in the rest of the grid, it is necessary to clear the fault as quick as possible.

HVDC vs HVAC

The electricity started to be used for energy transporting approximately 120 years ago, and the first HVDC link was put into operation 50 ago. So HVDC can be considered to be a consolidated technology, although in a continuous development due to the improvements in the power electronic area.

When it comes time to choose between HVAC and HVDC in energy transmission, some few aspects have to be taken in account:

- *Technical aspects*
    - In an HVCD system the power in the system power is almost kept constant, independently of the distance. However, in an HVAC system, the transmission capacity decreases with the distance, due to inductive effects.
    - In the case of having two systems, with different frequencies at the ends, it is unavoidable to use HVDC.
    - The energy transmission used in offshore cables is limited to short distances in HVAC, due to its high dielectric capacity. So in an offshore system, it is necessary the use HVDC. HVDCs are not affected by capacitive neither inductive parameter of the lines.

- *Economic aspects*
    - In general, the HVDC system has more direct costs than HVAC. However these costs are compensated for lower costs in the line transmission and less losses.

- *Environmental aspects*
    - The principal environmental reasons for which HVDC is preferable instead of HVAC, besides the visual impact, are reasons related to the magnetic field and the corona discharge.

PREVIOUS WORK

The faults are important incidents, which have been dealt with in several studies. Different ways for acting in a fault case have been presented in several thesis works.

For instance Lena Max's thesis presents that the increase of the wind power penetration in the electrical system has introduced new requirements to ensure a good operation of the grid. Wind farms should not be disconnected during a fault in the main grid. Since the power transmission to the grid decrease dramatically during the fault, the excess energy should be dissipated in order to avoid tripping of the wind farm and preventing an over voltage. The whole collection grid of the wind park was allowed to collapse for about 1 second.

One of the solutions is to reduce the output power of the wind turbines by using an internal breaker resistance or letting the excess energy be stored as rotational energy. The other solution is the use of a breaker resistance at the HVDC link. Whit this solution the DC collection grid will not be affected during grid faults, since the DC collection grid will not be affected.

However, this strategy is not possible in a meshed DC grid, here a fault must be cleared, without a collapse in the network voltage. (MAX, 2009)

THESIS OBJECTIVE

This thesis is a part of an ongoing work at the department of Energy and Environment regarding a meshed DC network equipped with wind energy installations. The goal of this work is to simulate a short-circuit fault in order to propose settings of the DC breaker, as well as the design, and to check that the operation is as expected.

The simulation will be accomplished by modelling the circuit in Matlab. This modelling will be done by two different methods: using S-function and SimPowerSystems.

CHAPTER 2

COLLECTION OF KNOWN USABLE THEORY

SYSTEM DESIGN REQUIREMENTS

A DC grid can be considered when more than two converter stations are interconnected on the DC side via DC cables or overhead lines in meshed or radial system.

The principal components in a DC grid, Figure 2.1, are:

- Converters AC/DC (rectifiers) and DC/AC (inverters)
- Conversion transformers
- Transport lines
- AC and DC filters

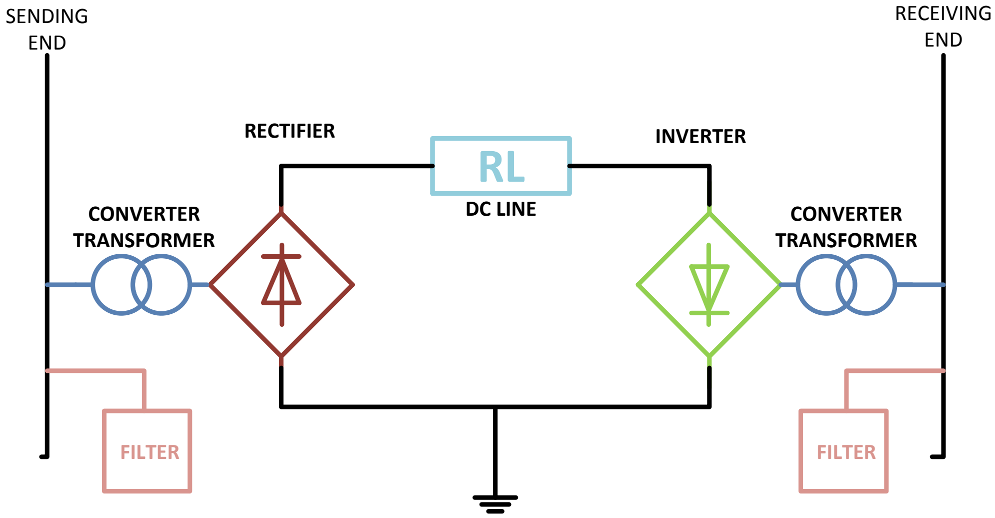


FIGURE 2.1, DC GRID

In order to control the active and reactive power, a system requirement is that the DC voltage should be above at least 80% of the nominal DC voltage. In order to avoid consequences such as voltage collapse or high currents it is necessary that the converters don't lose the control capability due to the low DC voltage.

A DC short-circuit fault is the worst case, which can make the DC voltage to suddenly be reduced to zero at the fault location. The effect of this voltage reduction can be reflected at other places of the DC grid depending mainly on the electrical distance to the fault location.

In order not to disturb converter stations, the fault has to be cleared within 5ms, for a DC grid connected by DC cables (JÜRGEN HÄFNER, 2011).

However, it is not only the DC grid system performance that requires fast DC switches, from the DC breaker design point it is also very crucial to realize a fast fault current breaking.

IGBT

The insulated-gate bipolar transistor or IGBT is a three-terminal power semiconductor device, and its most relevant characteristics are efficiency and fast switching.

The IGBT combines the simple gate-drive characteristics of the MOSFETs with the high-current and low-saturation-voltage capability of bipolar transistors by combining an isolated gate FET for the control input, and a bipolar power transistor as a switch, in a single device.

The characteristic IGBT curve represents the dependence between *I*c and *V*ce for each different value of *V*ge. The IGBT *(module 5SNA 0750G650300)* used in this project has a *V*ce,max=6500V and *I*c,max=750A. Its characteristic curve looks like the Figure 2.2.

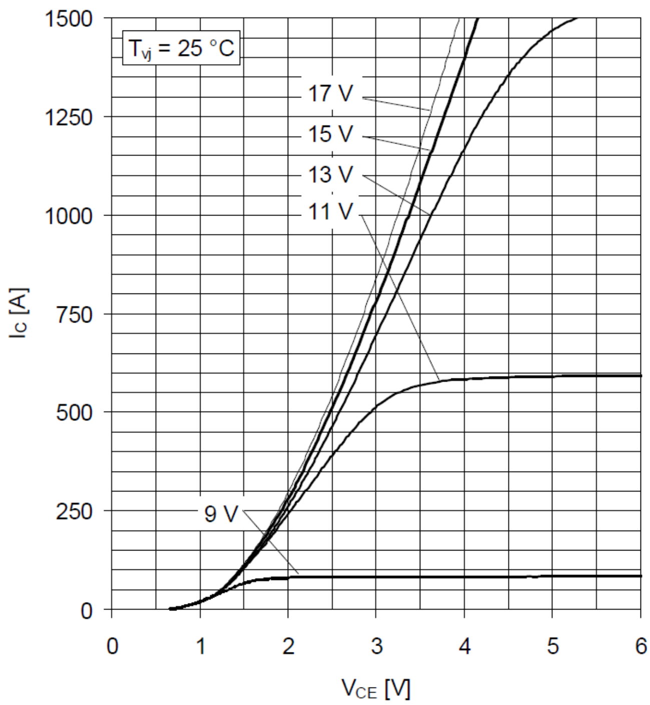


FIGURE 2.2, OUTPUT CHARACTERISTICS OF THE IGBT 5SNA 0750G650300 MODULE

Another important factor of the IGBTs is its thermal behaviour. In order to determine the temperature increase in the IGBT, it is necessary to know the thermal impedance. This thermal impedance is described in the data-sheet through the characteristic curve, Figure 2.2.

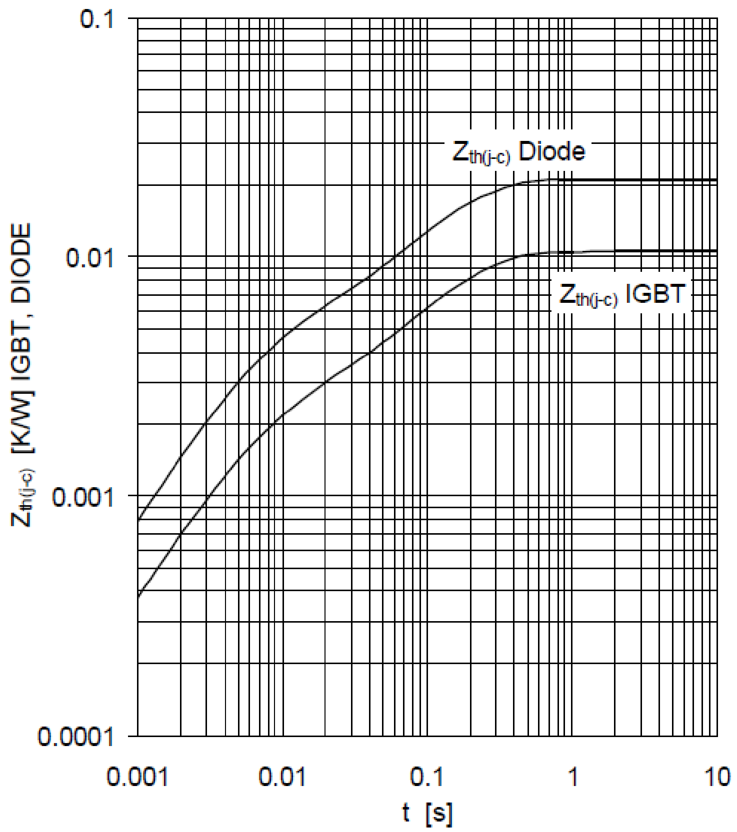


FIGURE 2.3, THERMAL IMPEDANCE VS TIME

ΔT= 60 °C is defined as the maximum temperature increase allowed. This limit establishes a value with which the IGBT can operate without being damaged.

PROPOSED HYBRID IGBT BREAKER

The purpose of this section is to illustrate the topology of the circuit used and the expected operation in normal operation as well as during the fault condition.

The circuit consists mainly of a piece of the DC network, including its line parameter and a hybrid DC breaker, and it is presented in the Figure 2.4.

The hybrid DC Breaker consists of two parallel branches: the auxiliary DC breaker and the main DC breaker, with corresponding control circuits.

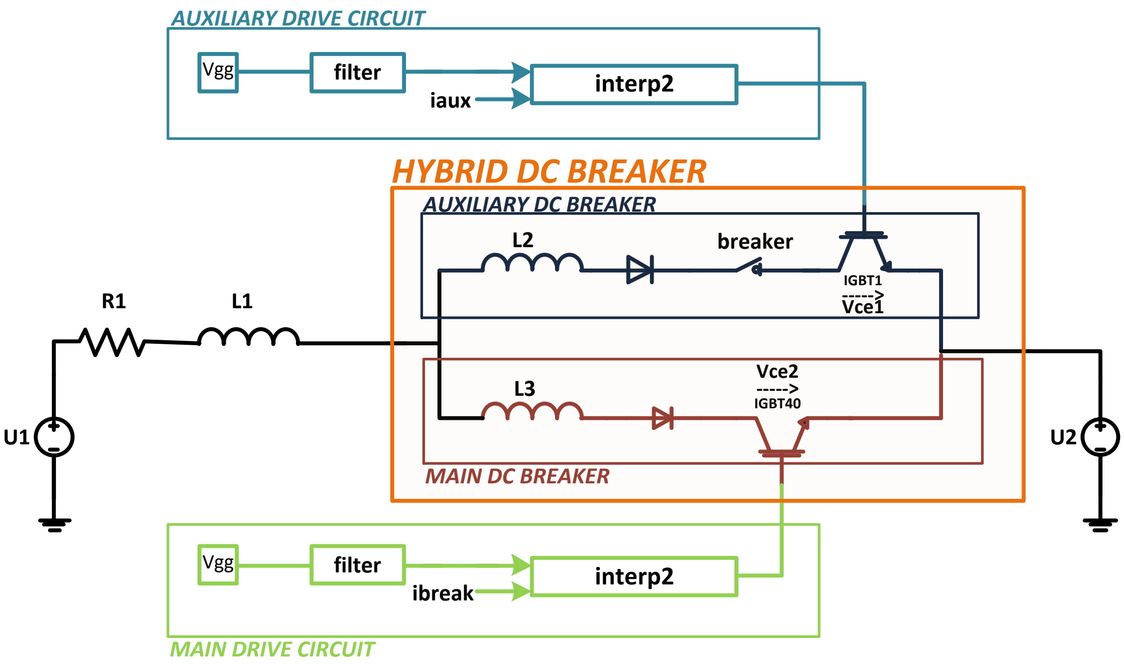


FIGURE 2.4, DC BREAKER CIRCUIT TOPOLOGY

During normal operation the auxiliary branch is conducting, but the IGBT (equivalent to 40IGBTs together) in the main branch is also prepared for operation, Figure 2.5. There is no current in the main branch, but the main IGBT will start to conduct when the voltage level over it reaches a certain value.

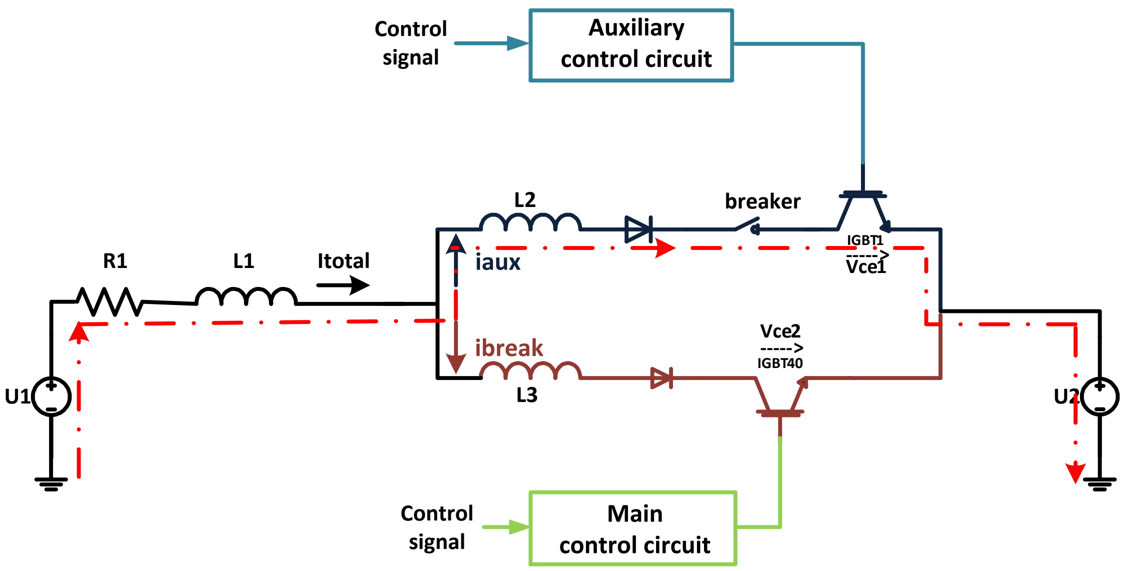


FIGURE 2.5, DC BREAKER IN NORMAL OPERATION

When a fault occurs, the auxiliary current raises fast. In the moment when the voltage over the main IGBT reaches this certain value, a commutation current starts to flow between both branches, Figure 2.6.

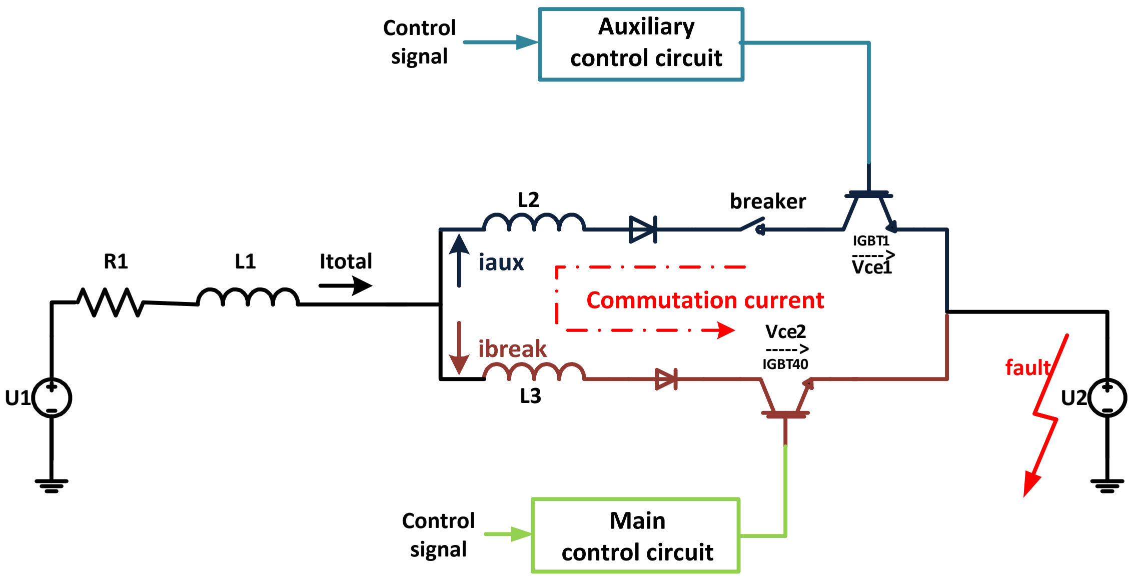


FIGURE 2.6, COMMUTATION CURRENT

When the auxiliary current is zero, the breaker is opened and all the current flows through the main branch, Figure 2.7.

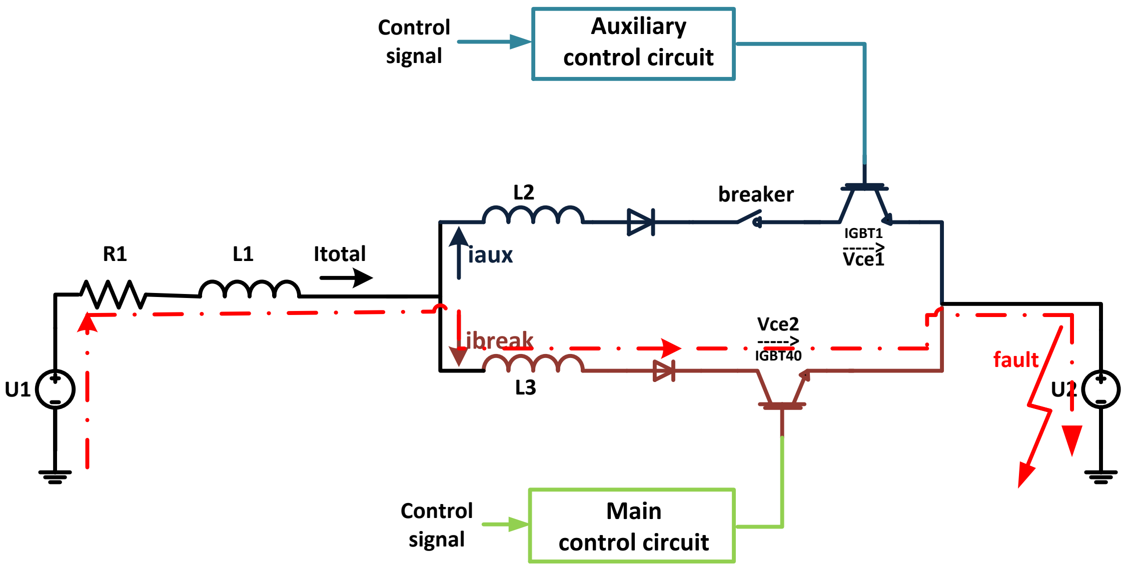


FIGURE 2.7, DC BREAKER WITH A FAULT CONDITION

The IGBT drive circuits have the following design, Figure 2.8:

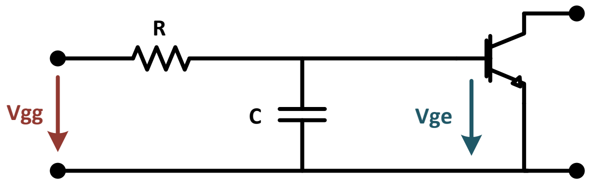


FIGURE 2.8, DRIVE CIRCUIT

CHAPTER 3

CASE SET-UP

OPERATION PROCESS

During normal operation (pre-fault operation), the current will only flow through the auxiliary branch.

The function of the mechanical breaker is to open the circuit when a fault appears. However, the mechanical breaker only can act properly when the current is approximately zero. Due to that the IGBT presence in the auxiliary branch is necessary. This IGBT is going to be represented by a DC controllable voltage source and its needed control circuit.

When a fault occurs, the current increases fast in the auxiliary branch, and when this current reaches a limit current value, a trigger signal is activated. Then *V*ge1 is decreased gradually through the drive circuit, from its initial value to zero, Figure 3.1.

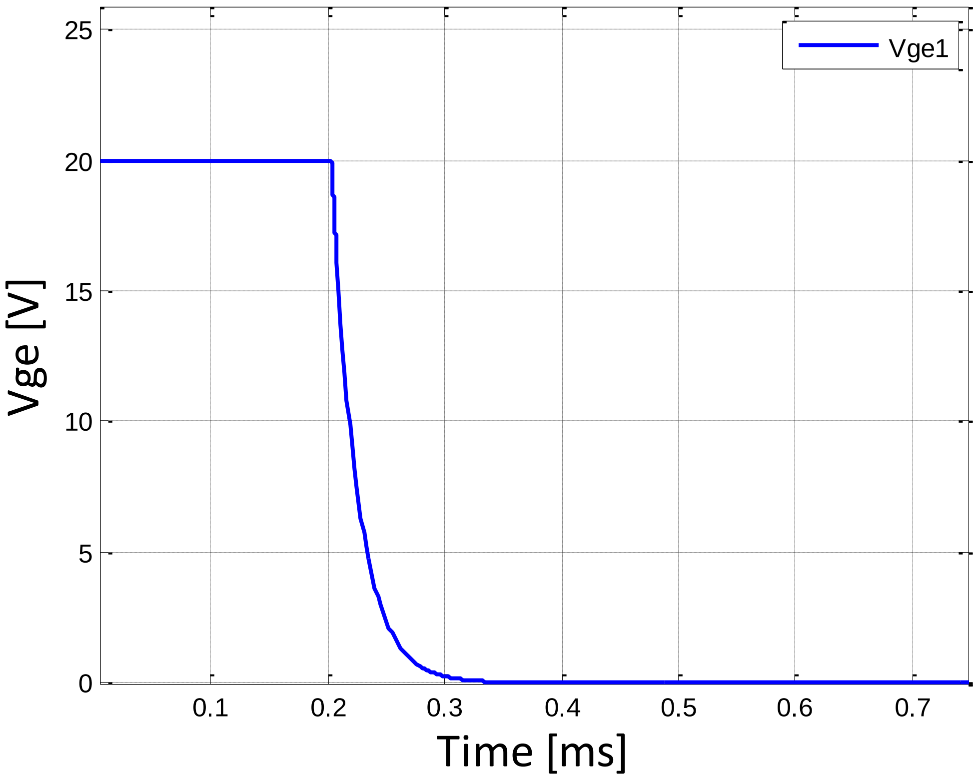


FIGURE 3.1, VGE VS TIME AUXILIARY DRIVE CIRCUIT

This value and *i*aux are the inputs to the *V*ce function. The Vce function has been stored as a look-up table using the characteristics of the IGBT.

This function then interpolates with the current and *V*ge, and provides a *V*ce value for each instant, Figure 3.2.

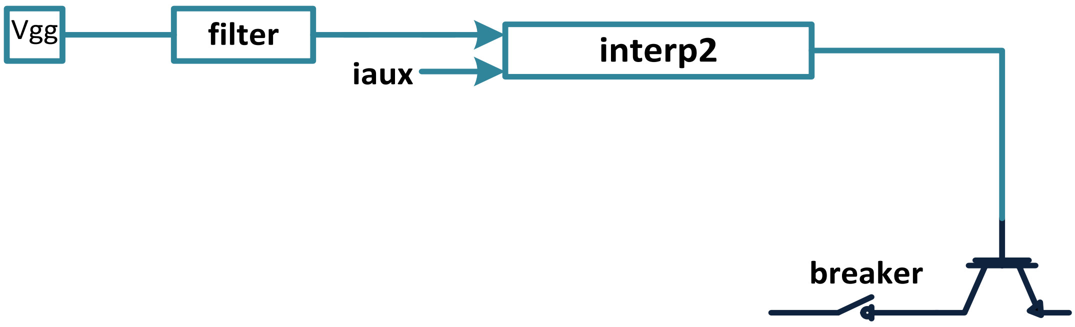


FIGURE 3.2, AUXILIARY DRIVE CIRCUIT

As a result of that, there is an increase in *V*ce1 and a decrease in the current. When the current is negligible, the mechanical breaker can open this branch.

At the same time, the current is to be commutated to the main branch, in order to bring the current in the auxiliary branch to zero.

This branch has a similar configuration to the one used in the auxiliary DC breaker, but now there is no mechanical breaker, instead, inside of the *V*ce function there are 40 IGBTs in series.

The main drive circuit will be activated with a separate trigger and gate-emitter voltage. Now, instead of decreasing the current, all the current has to flow through this branch. For this reason, *V*ge2 will be increased through its drive circuit, from its initial value to a maximum. This new trigger signal has to be activated a little bit later than the trigger signal in the auxiliary branch.

Furthermore, as soon as *i*aux is zero, this new trigger signal will be activated again, but in the opposite way, decreasing *V*ge2, from its maximum value to zero, Figure 3.3. The voltage over the 40 IGBTs will now increase to such a high value that the whole main current, *i*break, can fall to zero, the fault has now been cleared.

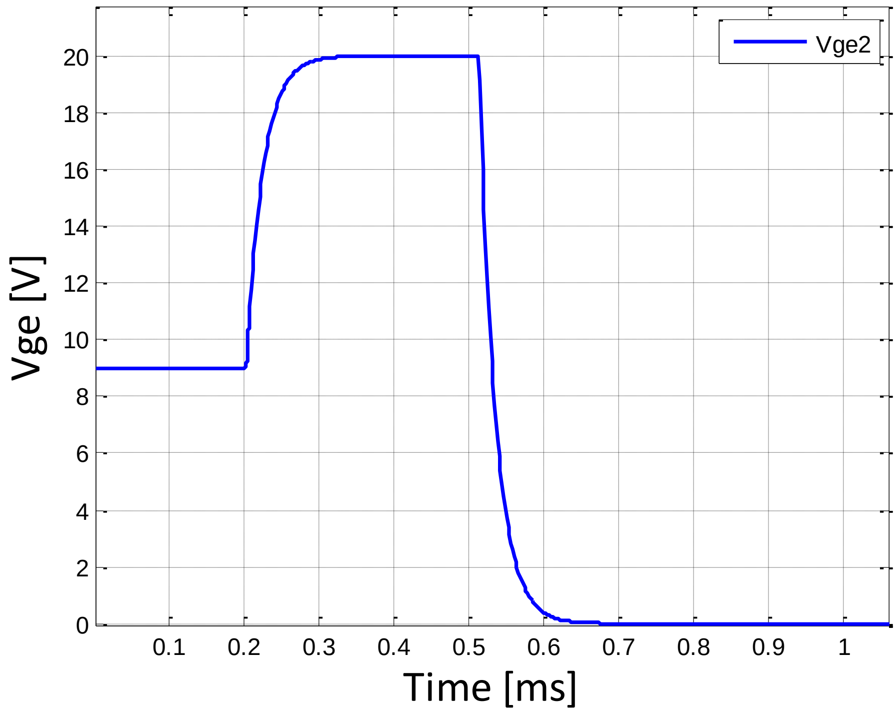


FIGURE 3.3, VGE VS TIME MAIN DRIVE CIRCUIT

Both drive circuit operations are shown in the Figure 3.4

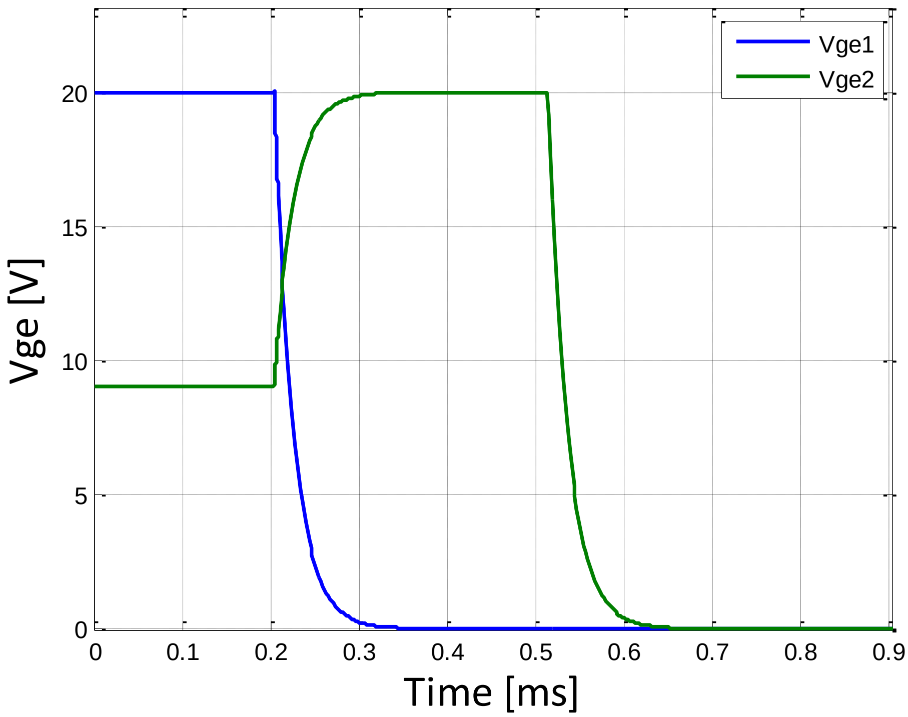


FIGURE 3.4, VGE VS TIME MAIN AND AUXILIARY DRIVE CIRCUITS

S-FUNCTION METHOD

This method consists of the sequence presented in Figure 3.5:

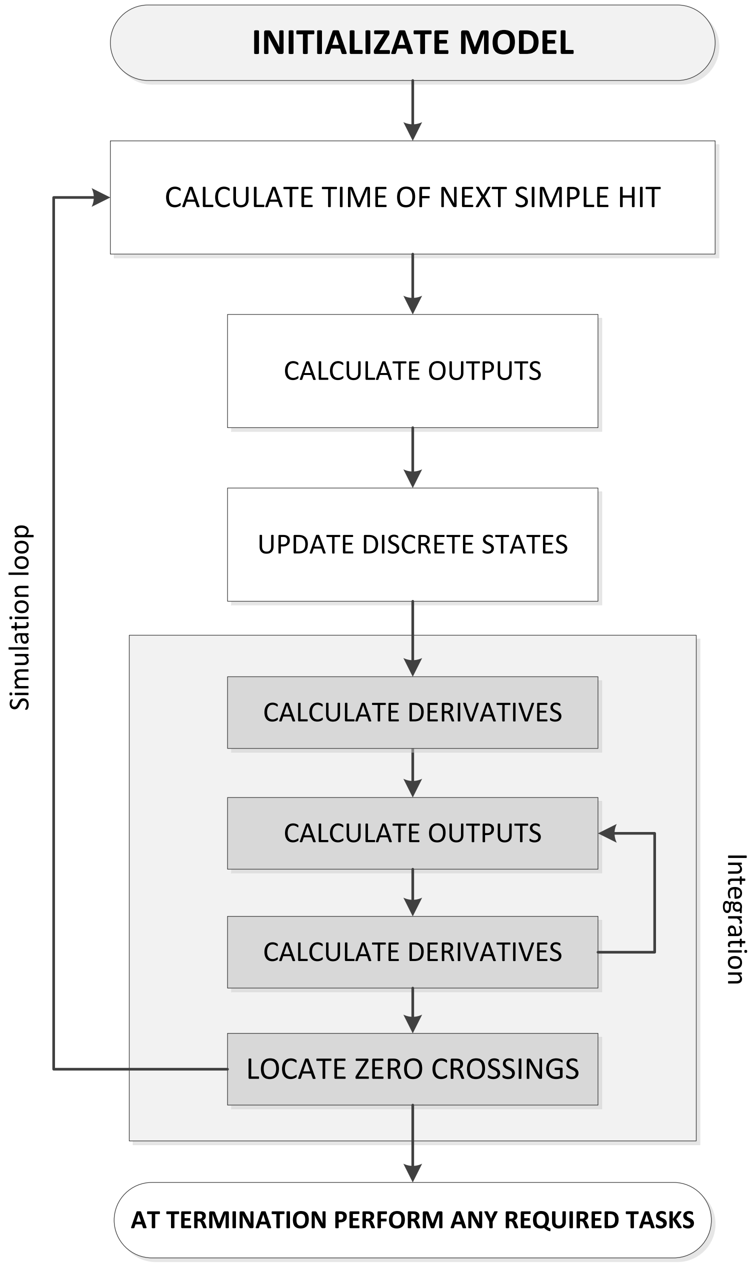


FIGURE 3.5, OVERVIEW OF S-FUNCTION

Now it is time to formulate the equations for the circuit, Figure 3.6.

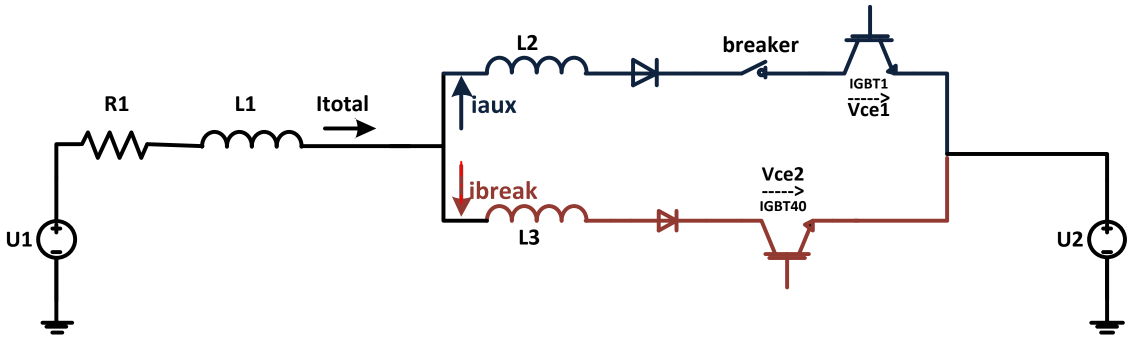


FIGURE 3.6, CIRCUIT TOPOLOGY

By performing a KVL the relation between voltage and current in the auxiliary branch can be found as,

$$U_1 = R_1 \cdot I_{total} + L_1 \cdot \frac{dI_{total}}{dt} + L_2 \cdot \frac{di_{aux}}{dt} + V_{ce1} + U_2.. \tag{3.1}$$

Doing the same with the main branch gives

$$U_1 = R_1 \cdot I_{total} + L_1 \cdot \frac{dI_{total}}{dt} + L_3 \cdot \frac{di_{break}}{dt} + V_{ce2} + U_2 \tag{3.2}$$

and between both branches,

$$L_2 \cdot \frac{di_{aux}}{dt} + V_{ce1} = L_3 \cdot \frac{di_{break}}{dt} + V_{ce2} \tag{3.3}$$

$$\frac{di_{aux}}{dt} = \frac{1}{L_2}\left[L_3 \cdot \frac{di_{break}}{dt} + V_{ce2} - V_{ce1}\right] \tag{3.4}$$

$$\frac{di_{break}}{dt} = \frac{1}{L_3}\left[L_2 \cdot \frac{di_{aux}}{dt} + V_{ce1} - V_{ce2}\right] \tag{3.5}$$

where

$$I_{total} = i_{aux} + i_{break} \tag{3.6}$$

$$\frac{dI_{total}}{dt} = \frac{d(i_{aux} + i_{break})}{dt} = \frac{di_{aux}}{dt} + \frac{di_{break}}{dt} \tag{3.7}$$

Combining the equations produces the following expresions

$$\frac{di_{aux}}{dt} = \frac{1}{L_1 + L_2 + \frac{L_1 \cdot L_2}{L_3}}\left[U_1 - U_2 - R_1(i_{aux} + i_{break}) + \frac{L_1}{L_3}V_{ce2} - (\frac{L_1}{L_3} + 1)V_{ce1}\right] \tag{3.8}$$

$$\frac{di_{break}}{dt} = \frac{1}{L_1 + L_3 + \frac{L_1 \cdot L_3}{L_2}}\left[U_1 - U_2 - R_1(i_{aux} + i_{break}) + \frac{L_1}{L_2}V_{ce1} - (\frac{L_1}{L_2} + 1)V_{ce2}\right] \tag{3.9}$$

Renaming the inductances

$$L_{12} = \frac{L_1}{L_2} \tag{3.10}$$

$$L_{13} = \frac{L_1}{L_3} \tag{3.11}$$

The final equations become:

$$\boldsymbol{\frac{di_{aux}}{dt} = \frac{1}{L_1 + L_2 + L_{13}L_2}[U_1 - U_2 - R_1(i_{aux} + i_{break}) + L_{13}V_{ce2} - (L_{13} + 1)V_{ce1}]} \tag{3.12}$$

$$\boldsymbol{\frac{di_{break}}{dt} = \frac{1}{L_1 + L_3 + L_{12}L_3}[U_1 - U_2 - R_1(i_{aux} + i_{break}) + L_{12}V_{ce1} - (L_{12} + 1)V_{ce2}]} \tag{3.13}$$

The equation for the drive circuits, Figure 3.7, can be formulated as:

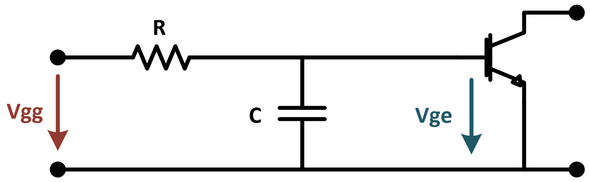


FIGURE 3.7, DRIVE CIRCUIT

$$I = \frac{V_{gg}}{R + \frac{1}{sC}} \tag{3.14}$$

$$V_{ge} = \frac{1}{sC} \cdot \frac{V_{gg}}{R + \frac{1}{sC}} = \frac{V_{gg}}{sCR + 1} \tag{3.15}$$

$$V_{ge}(sCR + 1) = V_{GG} \tag{3.16}$$

$$\frac{dV_{ge}}{dt} = \frac{1}{RC}\left[V_{gg} - V_{ge}\right] \tag{3.17}$$

The final equation can now be set up

$$\boldsymbol{\frac{dV_{ge}}{dt} = \frac{1}{RC}V_{gg} - \frac{1}{RC}V_{ge}} \tag{3.18}$$

SIMPOWERSYSTEMS METHOD

Simpowersystems provides fundamental building blocks to implement the circuit. With these blocks, which represent the different elements, and the physical connections it is possible to develop the system.

The circuit representation by this method looks like Figure 3.8

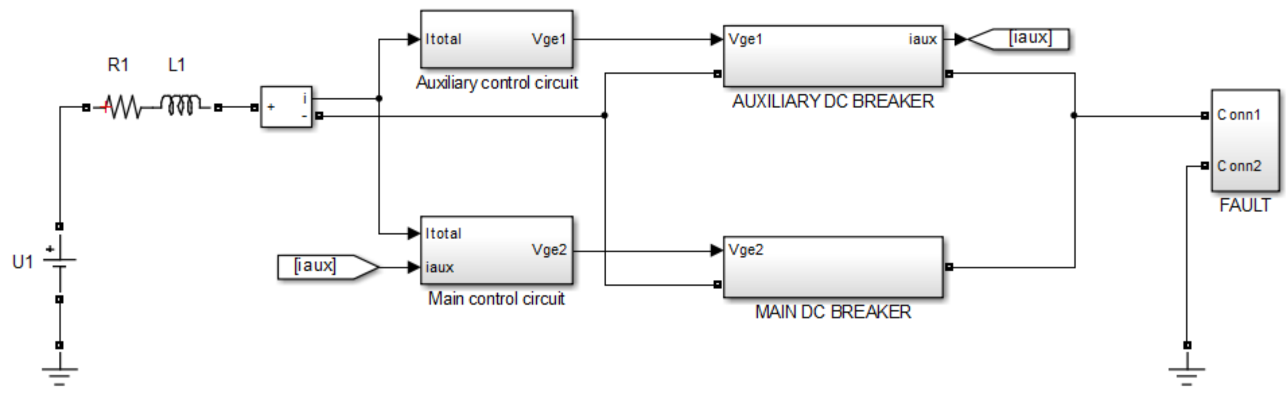


FIGURE 3.8, SIMPOWERSYSTEMS MODEL

Where the inside of the auxiliary DC breaker system is the circuit represented in the Figure 3.9

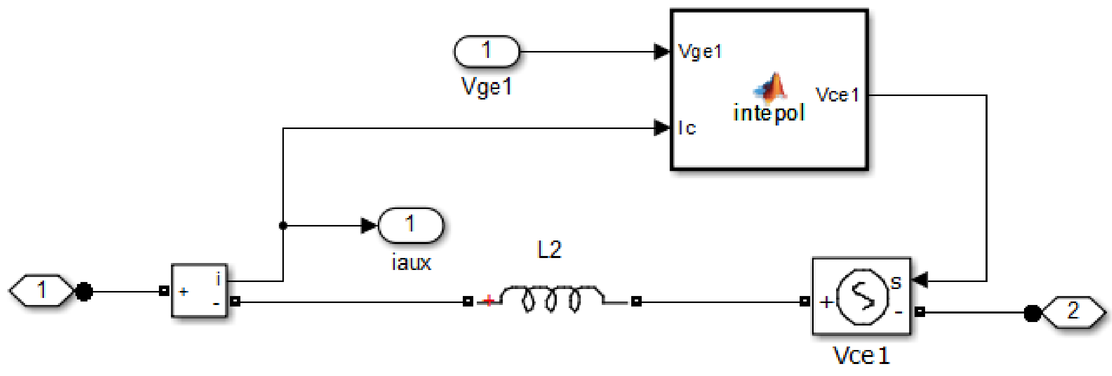


FIGURE 3.9, AUXILIARY DC BREAKER

And its control circuit, Figure 3.10

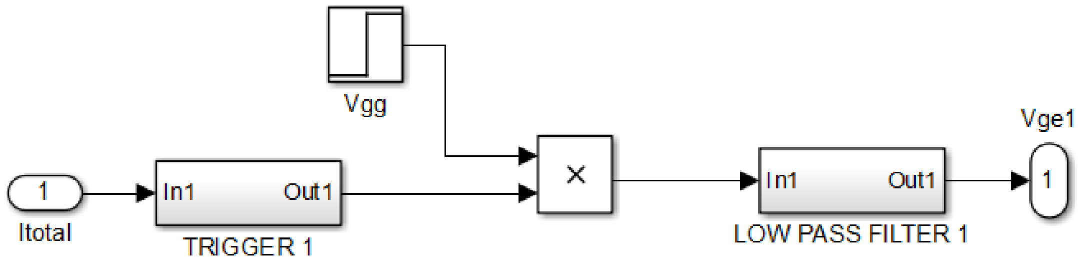


FIGURE 3.10, AUXILIARY CONTROL CIRCUIT

As well as inside the main DC breaker system, Figure 3.11

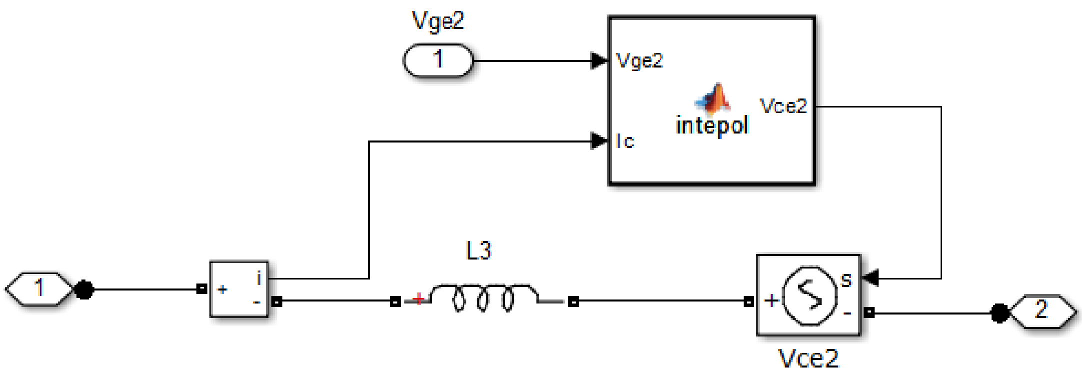


FIGURE 3.11, MAIN DC BREAKER

With its control circuit, Figure 3.12

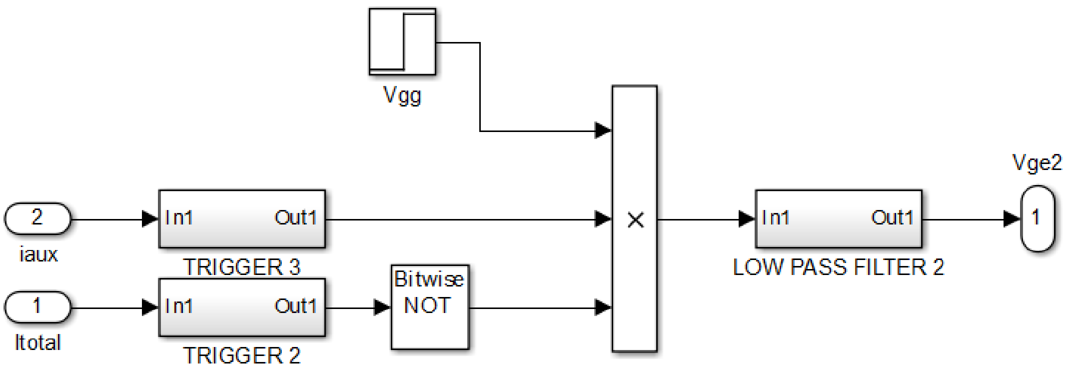


FIGURE 3.12, MAIN CONTROL CIRCUIT

CHAPTER 4
ANALYSIS PART

In this section the main results from the simulation is presented.

It is divided in two parts. The first corresponds to an ideal case, which will be simulated by the two methods (Simpowersystems and S-function).

The second part is a simulation with parameters corresponding to a real DC cable, which will be simulated only using the S-function method.

IDEAL CASE

In this case one ideal DC cable has been chosen. Its characteristics are presented in Table 4.1

TABLE 4.1, IDEAL DC CABLE CHARACTERISTICS

Single-core cables, nominal voltage 4 kV		
Branch inductances (L1, L2)	Inductance	Impedance
H	H	Ω
0.001	**0.001**	**0.25**

The main results correspond to the current waveform, where is possible to check if the behaviour is the expected, and the power representation, which is used to calculate the energy dissipation.

S-FUNCTION METHOD

The current waveforms are presented in Figure 4.1

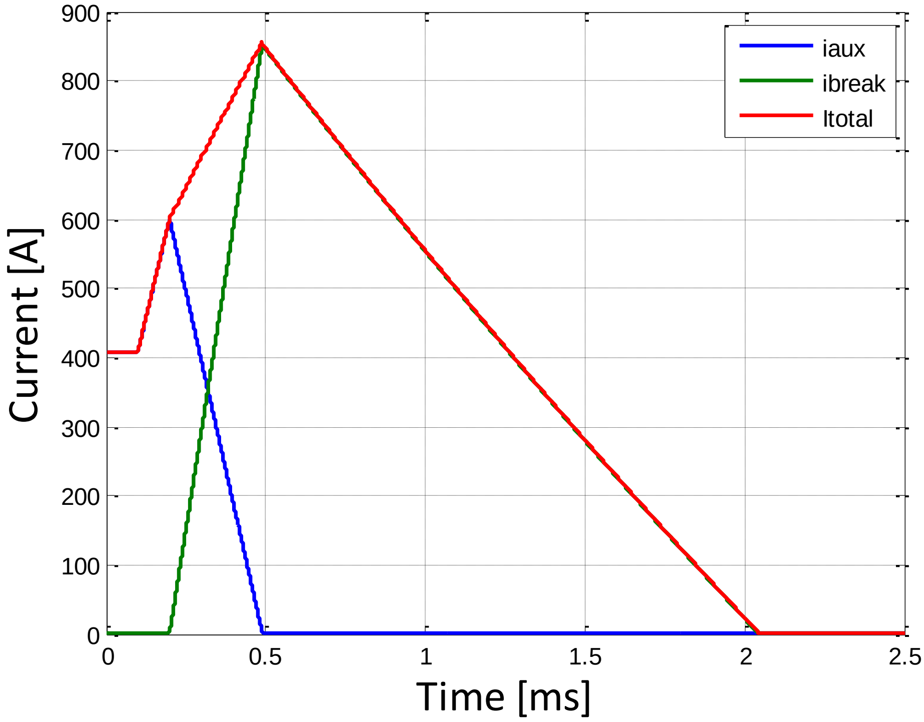


FIGURE 4.1, CURRENT VS TIME S-FUNCTION METHOD

The power over both IGBTs are shown in Figure 4.2

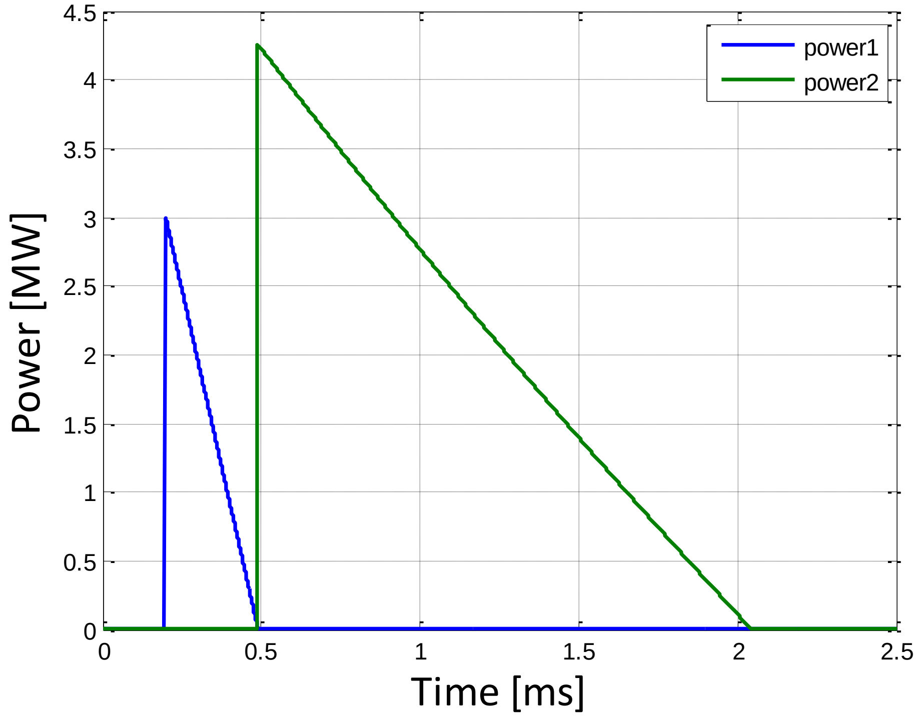


FIGURE 4.2, AUXILIARY AND MAIN POWER VS TIME S-FUNCTION METHOD

The main results are presented in Table 4.2

TABLE 4.2, IDEAL S-FUNCTION RESULTS

Imax	Power max 1	Energy 1	Power max 2	Energy 2
600.0815 A	2.999 MW	447.5634 J	4.255 MW	3214.9 J

SIMPOWERSYSTEMS METHOD

The current waveforms, Figure 4.3

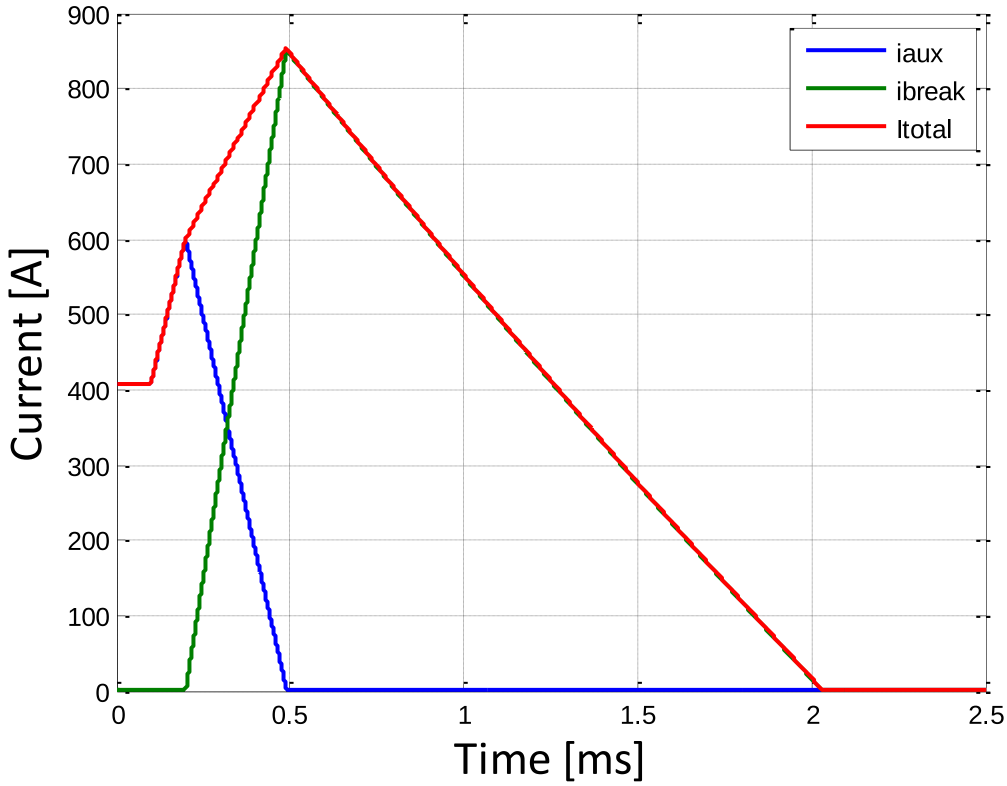


FIGURE 4.3, CURRENT VS TIME S-FUNCTION METHOD

and the power over both IGBTs in Figure 4.4

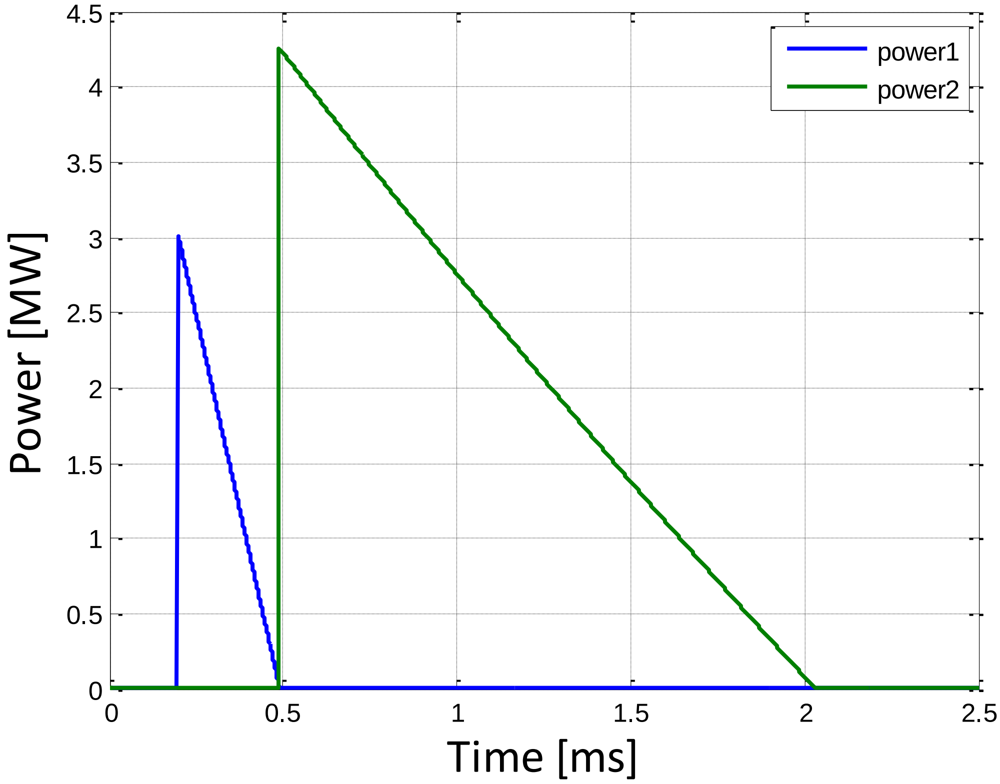


FIGURE 4.4, AUXILIARY AND MAIN POWER VS TIME S-FUNCTION METHOD

The main results are presented in Table 4.3

TABLE 4.3, IDEAL SIMPOWERSYSTEMS RESULTS

Imax	Power max 1	Energy 1	Power max 2	Energy 2
600.8 A	3.002 MW	448.951 J	4.255 MW	3188.1 J

COMPARISON OF METHODS

As it is possible to check, in all the figures, the circuit performance is as expected.

However, the obtained results from the each method have not been exactly the same. Only the auxiliary branch's ideal behaviour is studied by both methods, and the current increase is checked in depth, Figure 4.5 , it is possible to notice that the relation is almost the same.

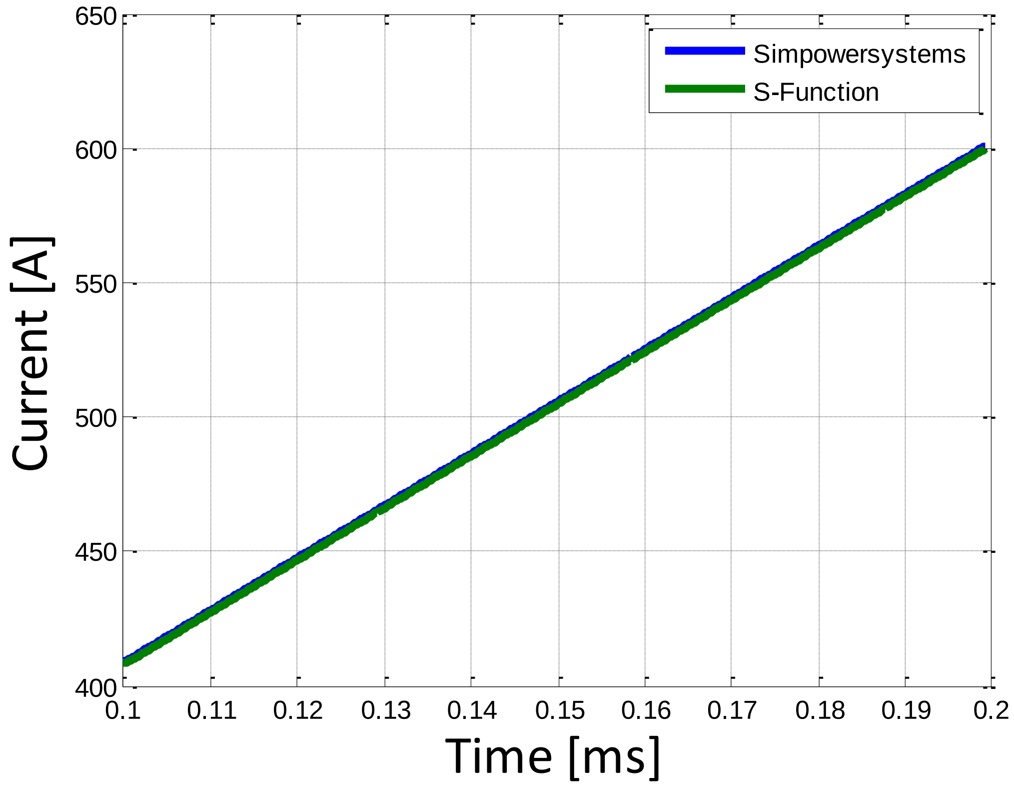


FIGURE 4.5, SIMPOWERSYSTEM VS S-FUNCTION

The trend lines are presented in the following equations,

$$y = 1935.6x + 214.27 \tag{5.1}$$

$$y = 1935.7 + 215.18 \tag{5.2}$$

This result entails that both method are reliable, nonetheless the simpowersystems presents more programming complications (saturation, simulation's tolerance and restrictions of parallel configuration). Due to these reasons, the S-Function method is used for the following case study simulations.

REAL CASE

In this case one real DC cable has been chosen from the data-sheet (ABB)

The resistance value is not given, so it must be calculated,

$$\frac{R}{L} = \frac{\rho}{A} = \frac{1.7 \cdot 10^{-8}}{2000 \cdot 10^{-6}} \cdot 1000 = 8.5\ m\Omega/\mathrm{km} \tag{5.3}$$

where

ρ: conductivity of copper

A: cross-section of conductor

The characteristics are presented in Table 4.4

TABLE 4.4, REAL DC CABLE CHARACTERISTICS

Single-core cables, nominal voltage 70 kV			
Cross-section of conductor	Branch inductances (L1, L2)	Inductance	Impedance
mm^2	H	mH/km	mΩ/km
2000	**0.001**	**0.29**	**8.5**

* The length of the cable simulated is 500km

The real line inductance for a length of 500 km is 0.145H. However, this value is too high, and the simulation presents some complications (slower simulation and more time necessary to clear the fault). One solution to decrease this value could be simulating a shorter cable, but the problem is that also the resistance would be affected with this method. A low resistance value has an effect on the current, which will be higher and it will be necessary to have more IGBTs. So, the decision taken is to implement the circuit with the original resistance and a lower inductance value. So, the decision taken is to implement the circuit with the original resistance and a lower inductance value. This value is 0.145mH, which is more similar to the branch inductances, and a good response is obtained a good response that allows the study of different settings.

The nominal voltage is now 70kV instead of 4kV as in the ideal case. This voltage increase has an effect on the current, which is higher now. For this reason it is necessary to modify the initial configuration. The current levels, Figure 4.6, impose to add 13 IGBT in parallel at least. So the final configuration is one IGBT in series and 14 in parallel in the auxiliary branch, and 20 in series with 14 in parallel in each in the main branch.

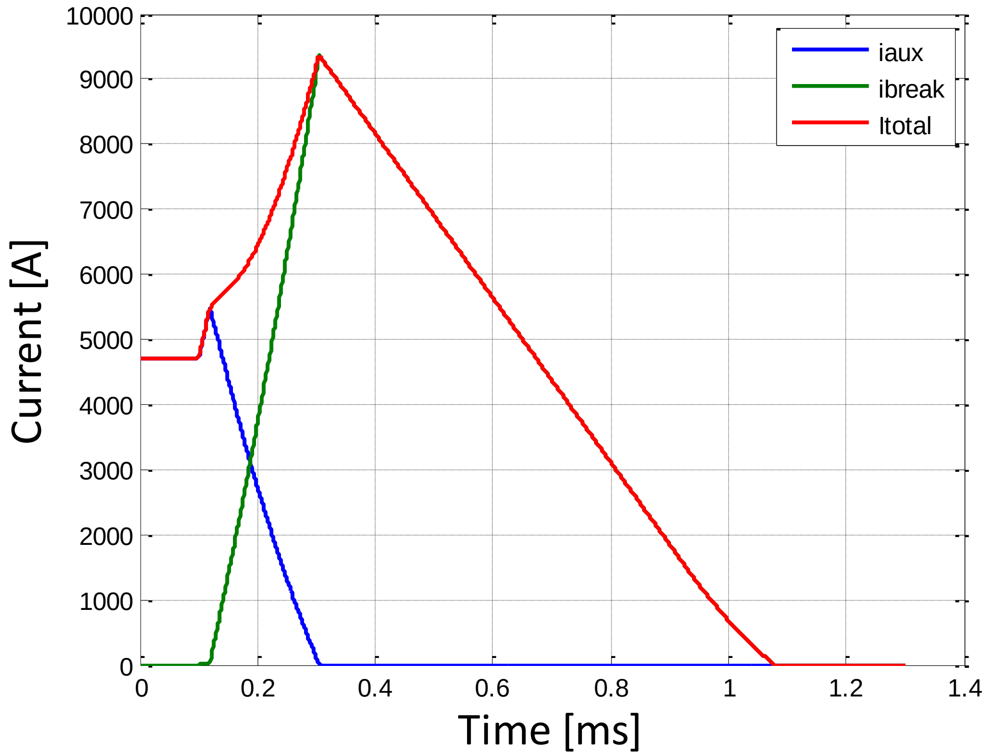


FIGURE 4.6, CURRENT VS TIME S-FUNCTION METHOD

The power over both IGBTs are shown in Figure 4.7

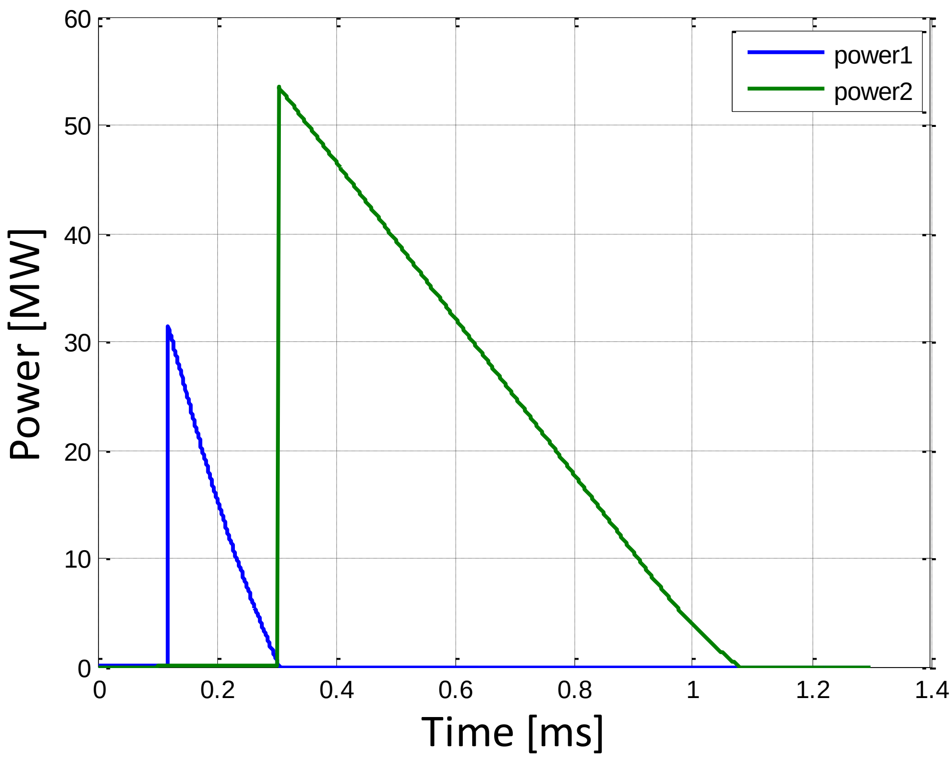


FIGURE 4.7, AUXILIARY AND MAIN POWER VS TIME S-FUNCTION METHOD

The main results are presented in Table 4.5

TABLE 4.5, MAIN RESULTS

Imax	Power max 1	Energy 1	Power max 2	Energy 2
5509.8 A	31.34 MW	2673.7 J	53.49 MW	19934 J

Analysing the thermal response is obtained that during 188µs the average power in the auxiliary IGBT is

$$P_{1,average} = \frac{Energy1}{time} = \frac{2673.7}{188} = 14.22\ MW \tag{5.4}$$

Extrapolating this value for 1ms, Z_{th}=0.0004 K/W *(module 5SNA 0750G650300)* and the power is 2.6737 MW. With these values is possible to calculate the temperature increase.

$$\Delta T = P \cdot Z_{th} = 2.6737 \cdot 400 = 1069.48\ ^{\circ}\mathrm{C} \tag{5.5}$$

As is possible to check, this value is too far from the limit. The conclusion is that even though this is the best configuration, it is not efficient if the thermal losses are considered.

In order to reduce the temperature increase it is necessary to reduce the current. For getting this objective three possible changes will be studied:

1. Add more IGBTs in parallel
2. Advance the trigger time in the main branch
3. Decrease the inductance values

Add more IGBTs in parallel

Since each IGBT has a Z_{th}=0.0004 K/W and the temperature limit increase is 60 °C, the maximum power is

$$P_{max,average} = \frac{\Delta T}{Z_{th}} = \frac{60}{400 \cdot 10^{-6}} = 150\ kW \tag{5.6}$$

This Z_{th} corresponds to 1ms, so if this value is extrapolated, the maximum energy allowed is

$$Energy_{max} = P_{max,averge} \cdot 1 \cdot 10^{-3} = 150\ J \tag{5.7}$$

This energy value is obtained by using 242 IGBTs at least.

The current waveforms look like Figure 4.8

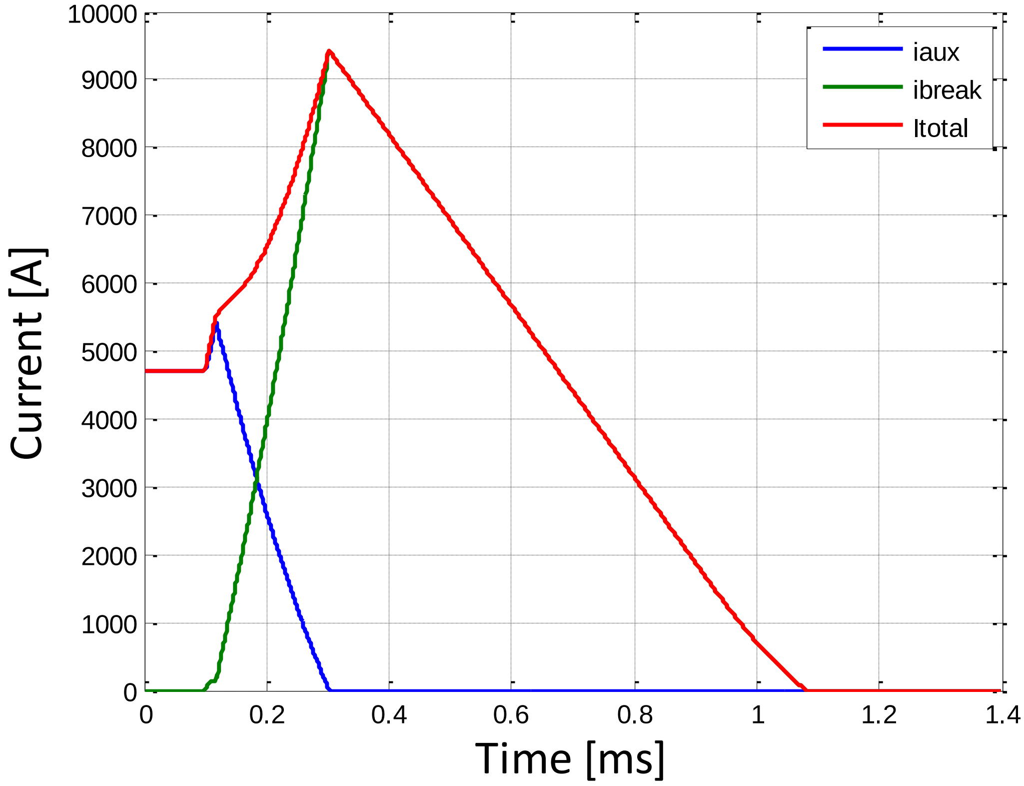


FIGURE 4.8, CURRENT VS TIME S-FUNCTION METHOD

and the power representation is shown in Figure 4.9

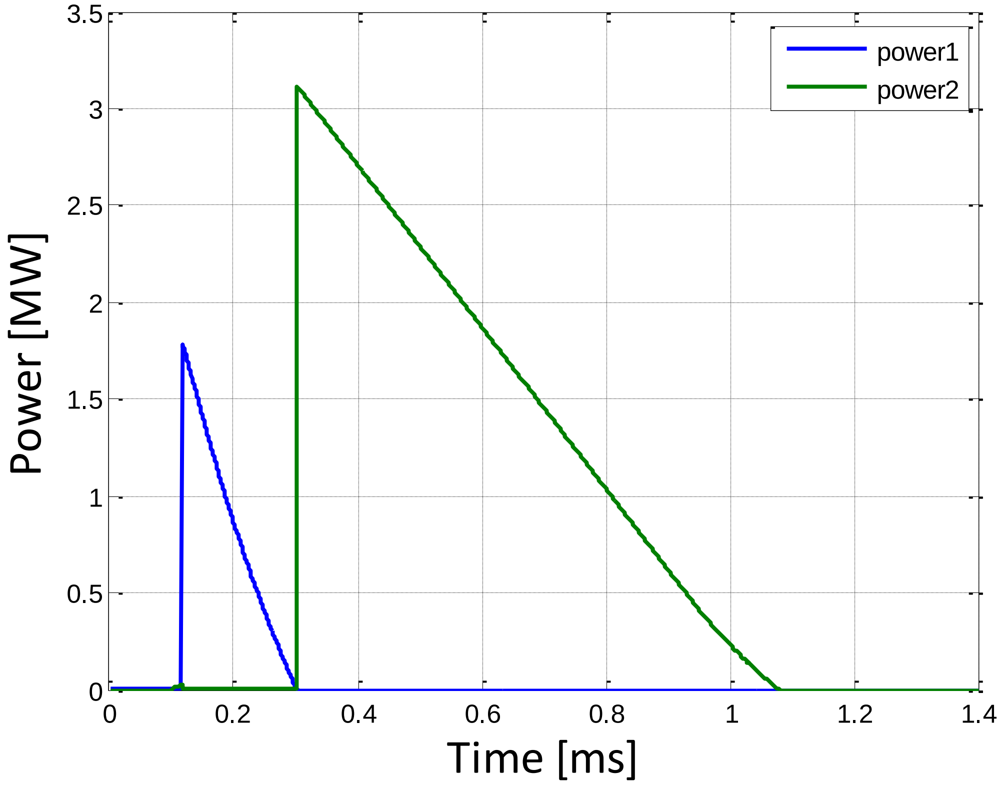


FIGURE 4.9, AUXILIARY AND MAIN POWER VS TIME S-FUNCTION METHOD

The main results are presented in Table 4.6

TABLE 4.6, MAIN RESULTS

Imax	Power max 1	Energy 1	Power max 2	Energy 2
5507.4 A	1.785 MW	150.0305 J	3.118 MW	1170.4 J

Analysing the thermal response, as is done in the previous case, is obtained that during 185µs the average power in the auxiliary IGBT is

$$P_{1,average} = \frac{Energy1}{time} = \frac{150.0305}{185} = 0.81\ MW \qquad (5.8)$$

Extrapolating this value for 1ms, the Z_{th}=0.0004 K/W and the power is 150.0305 kW. With these values is possible to calculate the temperature increase.

$$\Delta T = P \cdot Z_{th} = 0.150 \cdot 400 = 60\ °C \qquad (5.9)$$

ADVANCE THE TRIGGER TIME IN THE MAIN BRANCH

With only this technique it is not possible to get an efficient thermal system. However, combining this tactic with the previous one, it is possible to decrease the number of IGBTs used from 242 to 220.

The modifications in the current waveform can be observed in Figure 4.10.

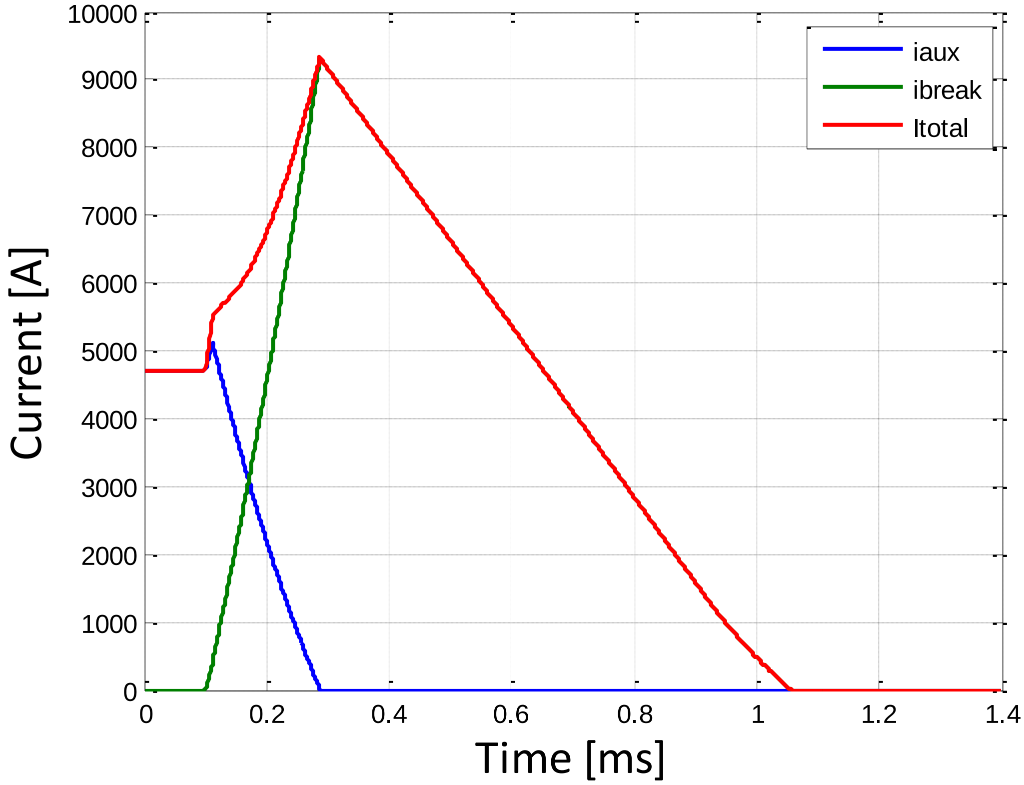


FIGURE 4.10, CURRENT VS TIME S-FUNCTION METHOD

The power representation, Figure 4.11,

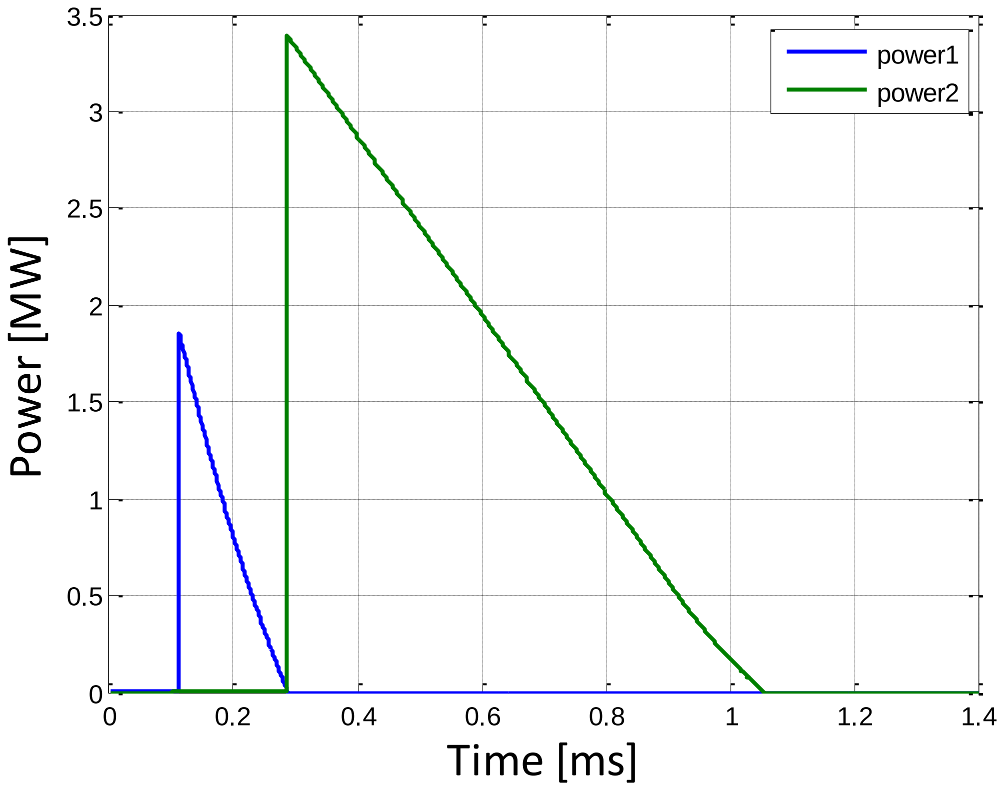


FIGURE 4.11, AUXILIARY AND MAIN POWER VS TIME S-FUNCTION METHOD

The main results are presented in Table 4.7

TABLE 4.7, MAIN RESULTS

Imax	Power max 1	Energy 1	Power max 2	Energy 2
5515 A	1.857 MW	149.3922 J	3.389 MW	1257.1 J

Analysing the thermal response is obtained that during 177µs the average power in the auxiliary IGBT is

$$P_{1,average} = \frac{Energy1}{time} = \frac{146.3922}{177} = 828.07\ kW \qquad (5.10)$$

Extrapolating this value for 1ms, the Z_{th}=0.0004 K/W and the power is 149.3922 kW. With these values is possible to calculate the temperature increase.

$$\Delta T = P \cdot Z_{th} = 0.14939 \cdot 400 = 59.757\ °C \qquad (5.11)$$

DECREASE THE INDUCTANCE VALUES

The last proposed tactic consists of decreasing the inductance values. If its initial values, 0.001H, are reduced to 0.065mH, the temperature increase is on the limit.

The current waveforms are presented in Figure 4.12

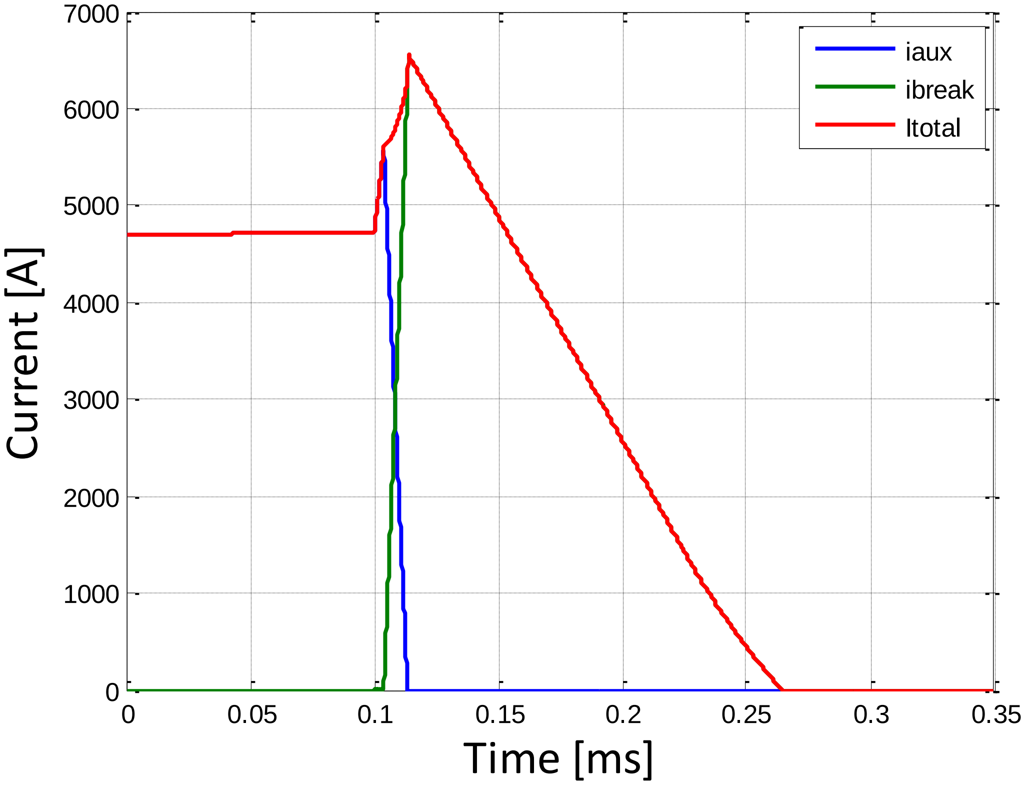


FIGURE 4.12, CURRENT VS TIME S-FUNCTION METHOD

The power over both IGBTs are shown in Figure 4.13

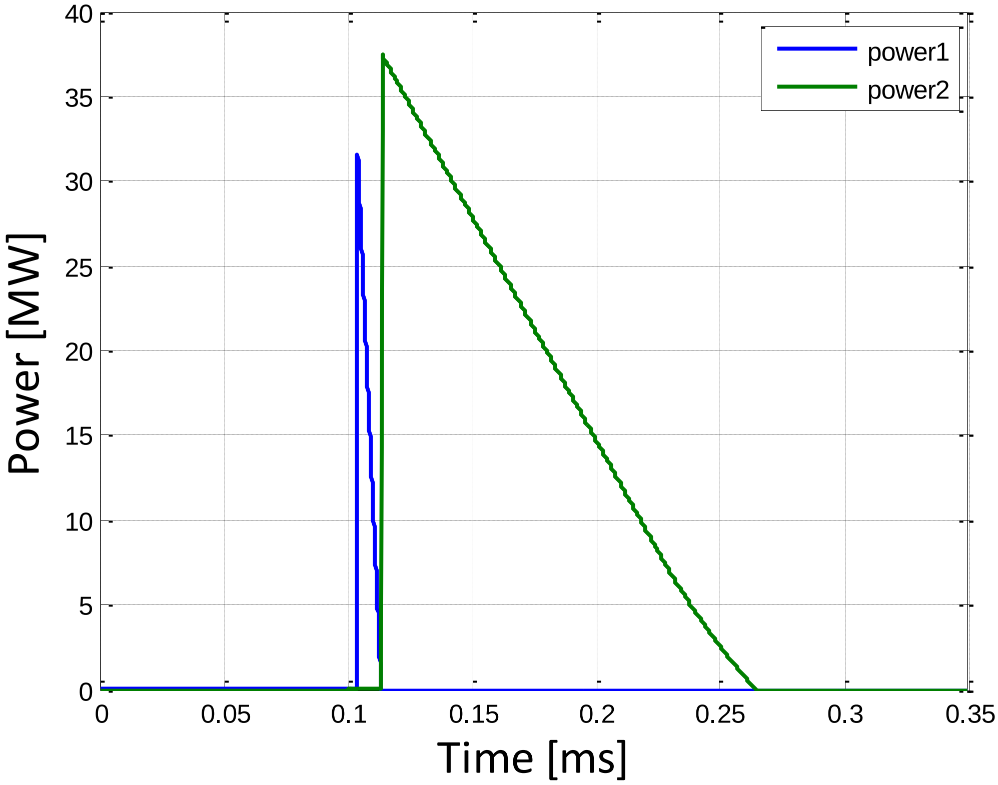


FIGURE 4.13, AUXILIARY AND MAIN POWER VS TIME S-FUNCTION METHOD

The main results are presented in Table 4.8

TABLE 4.8, MAIN RESULTS

Imax	Power max 1	Energy 1	Power max 2	Energy 2
5506 A	31.5 MW	149.1836 J	37.41 MW	2680.8 J

Analysing the thermal response is obtained that during 9.7µs the average power in the auxiliary IGBT is

$$P_{1,average} = \frac{Energy1}{time} = \frac{149.1836}{9.7} = 15.3797\ MW \qquad (5.12)$$

Extrapolating this value for 1ms, the Z_{th}=0.0004 K/W and the power is 149.1836kW. With these values is possible to calculate the temperature increase.

$$\Delta T = P \cdot Z_{th} = 0.149 \cdot 400 = 59.67\ °C \qquad (5.13)$$

CHAPTER 5
CONCLUSIONS

The last section is dedicated to a brief summary of the main conclusion and doing some proposals for possible future works.

RESULT FROM PRESENT WORK

According to the obtained results in the real case, the following statements are concluded. The configuration of 1x14 in the auxiliary branch and 20x14 in the main branch is the most optimal, in spite of the high thermal losses. Due to this more configurations are studied. As the main objective is to reduce the current in order to reduce the losses, the first modification is to add more IGBTs in parallel. This method is a fast way to fix the problem, but the minimum number of IGBTs necessary is too high. So this leads to the thought that this is not the best solution. If the trigger signal in the main branch is advanced, the commutation current starts earlier. With this method the losses in the auxiliary branch are decreased, but it is not enough to achieve an appropriated temperature increase. However, if both previously tactics are combined, the number of IGBTs needed can be lower.

Another solution is to change the breaker inductance values. If this value is decreased, the process will be faster, and the losses lower. But the problem with doing the system quicker is that the time step has to be lower, thus the simulation will be slower.

The aspect of time clearance, to which not much attention has been paid during this study, is completely controlled. All simulations have achieved a time clearance lower than 2ms. 2ms has been selected as a suitable time corresponding to a faster DC breaker.

After these conclusions, it can be determined that the design configurations are suitable, but the best model could be a combination between these three tactics.

FUTURE WORK

This report can be considered as a starting point into the DC breaker development. The next step could study further the influence of the cases presented in order to get the most suitable configuration.

In addition it could be useful get the right working of Simpowersystems, because this method makes easier to introduce modifications into the system, and its appearance is more similar physically to a real system.

The use of snubber circuits could be a possible improvement in order to provide a path to extinguish the interrupting current for the mechanical circuit breaker.

The final step would be implementing the hybrid DC breaker in a real physic system.

REFERENCES

ABB. *XLPE Cable Systems.*

JÜRGEN HÄFNER, B. J. (2011). Proactive Hybrid HVDC Breakers - A key innovation for reliable HVDC grids. Bologna.

MAX, L. (2009). *Design and Control of a DC Collection Grid for a Wind.* Goteborg.

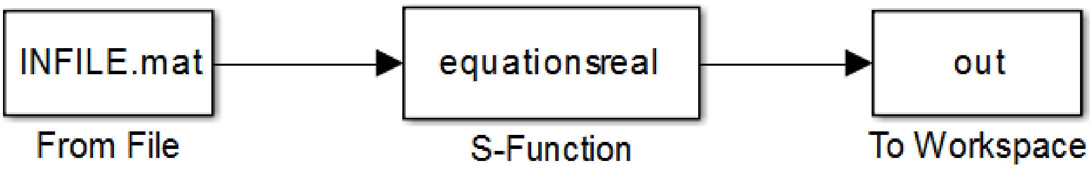
APPENDIX

S-FUNCTION CODE REAL CASE

```
%%%%%%%%%%%%%%%%%%%%%% main program %%%%%%%%%%%%%%%%%%%%%

%% clear all previous definitions
clear

% close all plot windows
close all
clc

%% Parameter definitions
R1=4.25;
L1=0.000145;
L2=0.001;
L3=0.001;
L12=L1/L2;
L13=L1/L3;
Lext=0;
Cge1=220e-9;
Cge2=220e-9;
Rg1=3;
Rg2=3;

%% Global variables
global iter1
iter1=0;
global iter2
iter2=0;
global iter3
iter3=0;
global Vgg
Vgg=20;
global Vgg1
Vgg1=20;
global Vgg2
Vgg2=9;
global T1
T1=0;
```

```
%% trigger values
Itrigger=5500;

%% look-up table parameters

% matrix X ( Vge values)
X=7:2:21;

% matrix Y ( Ic values)
Y=0:250:1500;

% matrix Z ( Vce values) (auxiliar branch)
Z1=[100000   0.625      0.625     0.625  0.625    0.625   0.625  0.625;
    100000   1000000  2.1        2       1.9375   1.875   1.875  1.875;
    100000   1000000  2.9        2.625  2.5       2.375   2.375  2.375;
    100000   1000000  1000000  3.125  2.9375  2.875   2.875  2.875;
    100000   1000000  1000000  3.625  3.375    3.25    3.25    3.25;
    100000   1000000  1000000  4.2     3.75     3.625   3.625   3.625;
    100000   1000000  1000000  5.25    4.125    3.875   3.875   3.875];

% matrix Z ( Vce values) (main branch)
Z2=20*[100000   0.625      0.625     0.625  0.625    0.625   0.625  0.625;
         100000   1000000  2.1        2       1.9375   1.875   1.875  1.875;
         100000   1000000  2.9        2.625  2.5       2.375   2.375  2.375;
         100000   1000000  1000000  3.125  2.9375  2.875   2.875  2.875;
         100000   1000000  1000000  3.625  3.375    3.25    3.25    3.25;
         100000   1000000  1000000  4.2     3.75     3.625   3.625   3.625;
         100000   1000000  1000000  5.25    4.125    3.875   3.875   3.875];


%% Initial values for the states, iaux_0, ibreak_0, Vge1_0, Vge2_0
xi=[4706;0;20;9];

%% setting up the simulation time and time step
Tstart=0.00;
Tfault=0.0001;
Tstop=Tfault+0.0012;
TimeStep=1e-6;
t=Tstart:TimeStep:Tstop;



%% formation of input file

u1=70000+0*t;
u2=50000*(1-floor(t/Tfault).^0.001);
```

```
plot(t,u1,t,u2),grid

indata=[t;u1;u2];
save INFILE indata

%% simulation call
sim('Blocksreal',[Tstart,Tstop]);

%% postprocessing
Postprocessreal
```




```
%%%%%%%%%%%%%%%%%%%%%% equationsreal %%%%%%%%%%%%%%%%%%%%%%


function [sys,x0,str,ts] =
equationsreal(t,x,u,flag,X,Y,Z1,Z2,Rg1,Rg2,Cge1,Cge2,R1,L1,L2,L3,L12,L13,Itrigger,xi)

switch flag,

 %%%%%%%%%%%%%%%%%%
 % Initialization %
 %%%%%%%%%%%%%%%%%%
 case 0,

[sys,x0,str,ts]=mdlInitializeSizes(t,x,u,flag,X,Y,Z1,Z2,Rg1,Rg2,Cge1,Cge2,R1,L1,L2,L3,L12,L13,It
rigger,xi);

 %%%%%%%%%%%%%%%
 % Derivatives %
 %%%%%%%%%%%%%%%
 case 1,
  sys=mdlDerivatives(t,x,u,flag,X,Y,Z1,Z2,Rg1,Rg2,Cge1,Cge2,R1,L1,L2,L3,L12,L13,Itrigger,xi);

 %%%%%%%%%%%
 % Outputs %
 %%%%%%%%%%%
 case 3,
  sys=mdlOutputs(t,x,u,flag,X,Y,Z1,Z2,Rg1,Rg2,Cge1,Cge2,R1,L1,L2,L3,L12,L13,Itrigger,xi);
```

```
%%%%%%%%%%%%%%%%%%%
% Unhandled flags %
%%%%%%%%%%%%%%%%%%%

case { 2, 4, 9 },
  sys = [];

%%%%%%%%%%%%%%%%%%%%
% Unexpected flags %
%%%%%%%%%%%%%%%%%%%%
otherwise
  error(['Unhandled flag = ',num2str(flag)]);

end

%%
%=============================================================================
===
% mdlInitializeSizes
% Return the sizes, initial conditions, and sample times for the S-function.
%=============================================================================
===
%
function
[sys,x0,str,ts]=mdlInitializeSizes(t,x,u,flag,X,Y,Z1,Z2,Rg1,Rg2,Cge1,Cge2,R1,L1,L2,L3,L12,L13,It
rigger,xi)

sizes = simsizes;
sizes.NumContStates  = 4;
sizes.NumDiscStates  = 0;
sizes.NumOutputs     = 6;
sizes.NumInputs      = 2;
sizes.DirFeedthrough = 0;
sizes.NumSampleTimes = 1;

sys = simsizes(sizes);
x0  = xi;
str = [];
ts  = [0 0];

% end mdlInitializeSizes
%%
%=============================================================================
===
% mdlDerivatives
% Return the derivatives for the continuous states.
```

```
%==========================================================================
===
%
function
sys=mdlDerivatives(t,x,u,flag,X,Y,Z1,Z2,Rg1,Rg2,Cge1,Cge2,R1,L1,L2,L3,L12,L13,Itrigger,xi)

global iter1
global iter2
global iter3
global Vgg1
global Vgg2
global T1

iaux=x(1);
ibreak=x(2);
Vge1=x(3);
Vge2=x(4);

U1=u(1);
U2=u(2);

iaux2=iaux/14;
ibreak2=ibreak/14;

%% Boundary condition auxiliar branch
if Vge1>21
    Vge1=21;
end

if Vge1<7
    Vge1=7;
end

if iaux2>1500
    iaux2=1500;
end

if iaux2<0
   iaux2=0;
end

if iaux<0
   iaux=0;
end
```

Apendix

```
%% Boundary condition main branch
if Vge2>21
    Vge2=21;
end

if Vge2<7
    Vge2=7;
end

if ibreak>1500
    ibreak=1500;
end

if ibreak<0
    ibreak=0;
end

if ibreak2>1500
    ibreak2=1500;
end

if ibreak2<0
    ibreak2=0;
end


%% equations

Vce1 = interp2(X,Y,Z1,Vge1,iaux2);
Vce2 = interp2(X,Y,Z2,Vge2,ibreak2);


if Vce1>80000
   Vce1=80000;
End

if Vce2>80000
   Vce2=80000;
end

diaux_dt =(1/(L1+L2+L13*L2))*(U1 - U2 - Vce1*(L13+1) + L13*Vce2 - R1*(iaux+ibreak));
dibreak_dt =(1/(L1+L3+L12*L3))*(U1 - U2 - Vce2*(L12+1) + L12*Vce1 -R1*(iaux+ibreak));
dVge1_dt =(-1/(Rg1*Cge1))*Vge1 + (1/(Rg1*Cge1))*Vgg1;
dVge2_dt =(-1/(Rg2*Cge2))*Vge2 + (1/(Rg2*Cge2))*Vgg2;

sys=[diaux_dt; dibreak_dt;
    dVge1_dt; dVge2_dt];
```

```
% end mdlDerivatives
%%
%==============================================================================
===
% mdlOutputs
% Return the block outputs.
%==============================================================================
===
%

function
sys=mdlOutputs(t,x,u,flag,X,Y,Z1,Z2,Rg1,Rg2,Cge1,Cge2,R1,L1,L2,L3,L12,L13,Itrigger,xi)

global iter1
global iter2
global iter3
global Vgg1
global Vgg2
global T1

iaux=x(1);
ibreak=x(2);
Vge1=x(3);
Vge2=x(4);

iaux2=iaux/14;
ibreak2=ibreak/14;

%% Boundary condition auxiliary branch
if Vge1>21
    Vge1=21;
end

if Vge1<7
    Vge1=7;
end

if iaux2>1500
    iaux2=1500;
end

if iaux2<0
   iaux2=0;
end

if iaux<0
```

```
    iaux=0;
end

%% Boundary condition main branch
if Vge2>21
    Vge2=21;
end

if Vge2<7
    Vge2=7;
end

if ibreak<0
    ibreak=0;
end

if ibreak2>1500
    ibreak2=1500;
end

if ibreak2<0
    ibreak2=0;
end

%% Trigger signal

Itotal = iaux+ibreak;

if (Itotal>Itrigger && iter1==0)
    global iter1
    global iter2
    global Vgg1
    global T1
    Vgg1=0;
    iter1=1;
    iter2=2;
    Imax=Itotal
    T1=t;
end

if (t>T1 && iter2==2)
    global Vgg2
    global iter2
    Vgg2=20;
    iter2=1;
end
```

```
if (iaux<20 && iter3==0)
   global Vgg2
   global iter3
   Vgg2=0;
   iter3=1;
end

%% outputs

Vce1 = interp2(X,Y,Z1,Vge1,iaux2);
Vce2 = interp2(X,Y,Z2,Vge2,ibreak2);

if Vce1>80000
   Vce1=80000;
end
if Vce2>80000
   Vce2=80000;
end

power1=iaux2*Vce1;
power2=ibreak2*Vce2;

sys = [t,iaux,ibreak,Itotal,power1,power2];


% end mdlOutputs


%%%%%%%%%%%%%%%%%%%%%%%%% postprocess %%%%%%%%%%%%%%%%%%%%%%%%%%

%% Variables
time_out=out(:,1);
iaux=out(:,2);
ibreak=out(:,3);
Itotal=out(:,4);
power1=out(:,5);
power2=out(:,6);

disp('****')
Tsample=time_out(2)-time_out(1);
disp('energy dissipation in switch 1')
Energy1=sum(power1)*Tsample
disp('****')
disp('energy dissipation in switch 2')
Energy2=sum(power2)*Tsample
disp('****')
```

```
time_out1=time_out*1e3;

figure
plot(time_out1,iaux,time_out1,ibreak,time_out1,Itotal,'LineWidth',2),grid
xlabel('Time [ms]','FontName','calibri','Fontsize',18,'HorizontalAlignment','center')
ylabel('Current [A]','FontName','calibri','Fontsize',18,'HorizontalAlignment','center')
legend('iaux','ibreak','Itotal')

figure
plot(time_out1,power1/1e6,'LineWidth',2),grid
xlabel('Time [ms]','FontName','calibri','Fontsize',18,'HorizontalAlignment','center')
ylabel('Power [MW]','FontName','calibri','Fontsize',18,'HorizontalAlignment','center')
legend('power1')

figure
plot(time_out1,power2/1e6,'LineWidth',2),grid
xlabel('Time [ms]','FontName','calibri','Fontsize',18,'HorizontalAlignment','center')
ylabel('Power [MW]','FontName','calibri','Fontsize',18,'HorizontalAlignment','center')
legend('power2')

figure
plot(time_out1,power1/1e6,time_out1,power2/1e6,'LineWidth',2),grid
xlabel('Time [ms]','FontName','calibri','Fontsize',18,'HorizontalAlignment','center')
ylabel('Power [MW]','FontName','calibri','Fontsize',18,'HorizontalAlignment','center')
legend('power1','power2')
```

SIMPOWERSYSTEM CODE IDEAL CASE

```
%%%%%%%%%%%%%%%%%%%%%%% initialitation %%%%%%%%%%%%%%%%%%%%%%%%
clear all
close all
clc

%% line parameters
```

```
R1=0.25;
L1=0.001;
L2=0.001;
L3=0.001;
L12=L1/L2;
L13=L1/L3;
Lext=0;
U1=4000;
U2=3897.825;
Cge=220e-9;
Rg=3;
Rg2=3;

%% trigger values
Itrigger=600;
Itrigger2=600;

%% gate-emitter voltage
Vgg=20;

%%%%%%%%%%%%%%%%%%% simulation parameters %%%%%%%%%%%%%%%%%%%%%
%% time settings

Tfault=0.0001;
Tstop=Tfault+0.002;
Tstepmax=1e-2;
Tstepmin=1e-10;







%%%%%%%%%%%%%%%%%%%%%%%% simulation %%%%%%%%%%%%%%%%%%%%%%%%%%%
sim('main')

disp('****')
Tsample=tsim(2)-tsim(1)
disp('energy dissipation in switch 1')
Energy1=sum(power1)*Tsample
disp('****')
disp('energy dissipation in switch 2')
Energy2=sum(power2)*Tsample
disp('****')

%%%%%%%%%%%%%%%%%%%%%%%% result plots %%%%%%%%%%%%%%%%%%%%%%%%

%% Current
tsim1=tsim*1e3;
figure
```

```
plot(tsim1,Itotal,tsim1,Iaux,tsim1,Ibreak,'LineWidth',2),grid
xlabel('Time
[ms]','FontName','calibri','Fontsize',18,'HorizontalAlignment',
'center')
ylabel('Current
[A]','FontName','calibri','Fontsize',18,'HorizontalAlignment','
center')
legend('Itotal','Iaux','Ibreak')


%% Power
power3=power1/(1e6);
power4=power2/(1e6);

figure
plot(tsim1,power3,'LineWidth',2),grid
xlabel('Time
[ms]','FontName','calibri','Fontsize',18,'HorizontalAlignment',
'center')
ylabel('power
[MW]','FontName','calibri','Fontsize',18,'HorizontalAlignment',
'center')
legend('power1')

figure
plot(tsim1,power4,'LineWidth',2),grid
xlabel('Time
[ms]','FontName','calibri','Fontsize',18,'HorizontalAlignment',
'center')
ylabel('power
[MW]','FontName','calibri','Fontsize',18,'HorizontalAlignment',
'center')
legend('power2')
```